EO-1 Technology Validation Report

Enhanced Formation Flying

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David Folta & John Bristow
NASA Goddard Space Flight Center
Greenbelt, Maryland.

Albin Hawkins & Greg Dell
a.i. solutions Inc.
Lanham, Maryland

NASA/GSFC

TABLE OF CONTENTS

	List of Illustrations	iv
	List of Tables	v
1.	INTRODUCTION	1
2.	TECHNOLOGY DESCRIPTION	2
	2.1 Enhanced Formation Flying (EFF) Description	2
	2.2 Software Architecture	2
	2.3 Algorithm Modes	3
	2.4 ΔV Computations and Quantized Maneuvers	3
	2.5 Folta-Quinn Algorithm Control	4
	2.6 Formation Flying Orbital Mechanics	4
3.	TECHNOLOGY VALIDATION	5
	3.1 Ground Test Verification	5
	3.1.1 AutoCon Executive and Fuzzy Logic Validation	5
	3.1.2 Required data/necessary measurements	5
	3.1.3 Approach	6
	3.1.4 Testing Results	6
	3.1.5 Supporting Integration and Test (I&T) Data	6
	3.1.6 Rationale	7
	3.2 EFF Onboard Validation	7
	3.2.1 Validation of Interface and Algorithm	7
	3.2.2 Validation Results and Period of Performance	9
	3.2.3 Functional Validation of Modes 1 and 2	10
	3.2.4 Functional Propagation Comparisons	13
	3.2.5 Autonomous Maneuver Validation Results	13
	3.2.6 Autonomous Propagation Comparisons	14
	3.2.7 Independent Performance Assessment: EO-1 Formation History of Relative Motion and Keplerian Orbit Parameters	15
4.	APPLICATION POSSIBILITIES	17
5.	TECHNOLOGY INFUSION OPPORTUNITIES	17

6. LESSONS LEARNED 18

7. SUMMARY 19

8. TECHNICAL CONCLUSIONS 19

9. REFERENCES 20

LIST OF ILLUSTRATIONS

Figure No.		Page
1	NASA's EO-1 in Formation with Landsat-7	1
2	EFF Functional Diagram	2
3	EFF Commandable Modes	3
4	Orbit Mechanics of EO-1 Formation Flying	4
5	EFF Ground Validation	6
6	Percentage Difference in EO-1 Onboard and Ground Absolute ΔVs	11
7	Difference in EO-1 Onboard and Ground Absolute ΔVs	11
8	Absolute Difference in 3-D Onboard and Ground ΔVs	11
9	Percentage Difference in 3-D Onboard and Ground ΔVs	12
10	Percentage Difference in Original Algorithm and Onboard	12
11	Target and Desired Propagation Position Differences	15
12	Relative Radial vs. Alongtrack Separation	15
13	Ground Track Separation	15
14	Alongtrack Separation vs. Elapsed Time	16
15	Semimajor Axis Profiles	16
16	Eccentricity vs. Elapsed Time	16
17	Eccentricity vs. Arg of Periapsis	16

LIST OF TABLES

Table No.		Page
1.	Supporting I&T Hardware and Software	7
2.	Validation Test Completion	9
3.	Propagation Mean and Standard Deviation for Desired State Computation	13
4.	Quantized Maneuver Comparisons	15
5.	Three-Axis Maneuver Comparisons	15

1. INTRODUCTION

NASA's first-ever autonomous formation flying mission has been successfully demonstrated. With the launch of NASA's Earth Observer-1 satellite, called EO-1, NASA's Goddard Space Flight Center located in Maryland demonstrated the capability of satellites to react to each other and maintain a close proximity without human intervention. This technology is called Enhanced Formation Flying (EFF). This advancement allows satellites to autonomously react to each other's orbit changes quickly and more efficiently. It permits scientists to obtain unique measurements by combining data from several satellites rather than flying all the instruments on one costly satellite. It also enables the collection of different types of scientific data unavailable from a single satellite, such as stereo views or simultaneously collecting data of the same ground scene at different angles.

Formation Flying as seen in figure 1 is exactly that, satellites flying in a predetermined formation, and maintained in that formation by using onboard control. Therefore, when one satellite moves, the others move to coordinate their measurements. EO-1 was launched this past November as a technology mission designed to fly in formation with another NASA satellite called Landsat-7. Both satellites carry instruments that enable scientists to study high-resolution images and climatic trends in the Earth's environment. The EO-1 satellite flies only 60 seconds (450 kilometers) behind Landsat-7 and maintains the separation within 2 seconds. This separation is necessary for EO-1 to observe the same ground location through the same atmosphere region. It also demonstrates significantly improved return of science data. The mission allows engineers to compare technological advances made in ground observing instruments that are smaller, cheaper, and more powerful. EO-1 also demonstrates technologies for propulsion, onboard processing, and data storage.

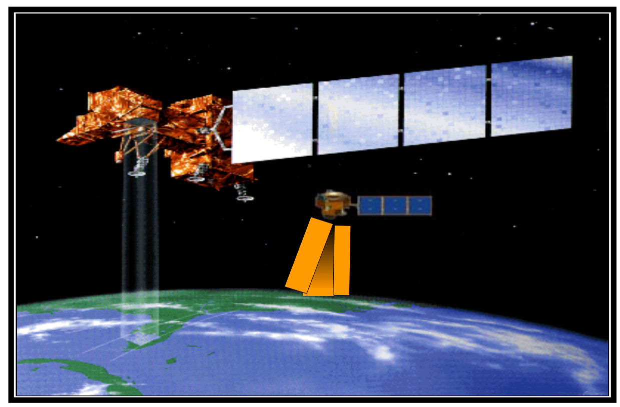

Figure 1. NASA's EO-1 in Formation with Landsat-7

Previously, satellites did not communicate directly with each other, did not plan and execute orbital maneuvers onboard, nor were they equipped to autonomously accommodate the actions of any other satellite in support of a desired scientific experiment. Onboard EO-1 is an advanced technological controller that is capable of autonomously planning, executing, and calibrating satellite orbit maneuvers. On EO-1 it is used for the computation of maneuvers to maintain the separation between the two satellites. The idea and mathematical algorithm for this NASA first was developed by Dave Folta, John Bristow, and Dave Quinn, Aerospace Engineers at the Goddard Space Flight Center (GSFC). It is designed as a universal 3-Dimensional method for controlling the relative motion of multiple satellites in any orbit. Their idea was then combined with a new flight software that is the predecessor of a GSFC sponsored commercial software call FreeFlyer produced by Lanham, MD based *a.i.-solutions inc*. This flight software provides for the ingest of real-time navigation data from the onboard Global Positioning System (GPS), the transfer of data from the maneuver algorithm for maneuver commands, onboard predictions of where the satellites will be in the future, the necessary attitude pointing, and actual onboard commanding of the thruster firings.

Because maneuver calculations and decisions can be performed onboard the satellite, the lengthy period of ground-based planning currently required prior to maneuver execution will eventually be eliminated. The system is also modular so that it can be easily extended to other mission objectives such as simple orbit maintenance. Furthermore, the flight controller is designed to be compatible with various onboard navigation systems.

Formation flying technologies are primarily concerned with the maintenance of the relative location between many satellites. Much shorter and more precise baselines can be established between the satellites. The satellites can then be combined as part of a "virtual satellite" that should provide previously unobtainable science data using mass produced, single-string, relatively cheap satellite. Multiple scientific instruments often present competing and conflicting requirements on a satellite design and its operation. So much science at stake for a single satellite often requires a great deal of onboard redundancy, which imposes its own overhead on the design process. Separating scientific payloads onto several simpler single-string satellites can accomplish the same complex missions without the added design and operational overhead, while risking only one payload at a time. The proposed approach for onboard formation control will enable a large number of satellites to be managed with a minimum of ground support. The result will be a group of satellites with the ability to detect errors and cooperatively agree on the appropriate maneuver to maintain the desired positions and orientations.

Another reason to use formations is due to the sensitivity of scientific instruments, which can often be increased by expanding the effective observation baselines (separation distances). This can be achieved by distributing the scientific instruments over many separate satellites. The formation flying technologies flown onboard EO-1 makes these missions routine and cost effective.

Since this technology is now fully developed and demonstrated, synchronous science measurements occurring on multiple space vehicles will become commonplace and the concept of Earth observing ‘virtual platforms’ will become a reality. In the process, this technology enables the development of autonomous rendezvous. Scientific payloads could be launched from any launch vehicle, rendezvous with and join a formation already in place, and then autonomously maintain this condition or respond to specific requests for science data collection by altering its own orbit. Thus, this technology addresses all of the NASA directives to build revolutionary satellites that are better, faster, and cheaper.

2. TECHNOLOGY DESCRIPTION

2.1 ENHANCED FORMATION FLYING (EFF) DESCRIPTION

Enhanced Formation Flying (EFF) is a new autonomous onboard technology, which features flight software that is capable of autonomously planning, executing, and calibrating routine spacecraft orbital maneuvers. The autonomous formation flying control software (the executive) is called AutoCon™ and builds on GSFC Guidance, Navigation, and Control (GN&C) existing capabilities for the maneuver planning, calibration, and evaluation tasks. AutoCon™ can also use a fuzzy control engine, ideal for this application because it can easily handle conflicting constraints between spacecraft subsystems. As part of the AutoCon™ executive system, a maneuver planning algorithm called the Folta-Quinn (FQ) algorithm was implemented. The output of the FQ algorithm provides the AutoCon system with a maneuver ΔV and attitude information. The AutoCon™ system then takes this maneuver data and computes a maneuver duration and attitude control. The maneuver start, duration, and attitude are the generated as part of the overall absolute time sequence. This whole process, from data ingest and propagation, to maneuver calculations is call Enhanced Formation Flying (EFF).

2.2 SOFTWARE ARCHITECHTURE

The EFF flight control system ingests data from EO-1 sensors and subsystems such as propulsion, navigation, and attitude data. It then autonomously generates, analyzes, and executes the maneuvers required to initialize and maintain the formation between Landsat-7 and EO-1. Figure 2 shows a functional diagram of EFF and the AutoCon™ system. Because these calculations and decisions are performed onboard the spacecraft, the lengthy period of ground-based planning currently required prior to maneuver execution will be eliminated. The system is general and modular so that it can be easily extended to future missions. Furthermore, the AutoCon™ flight control system is designed to be compatible with various onboard navigation systems (i.e. GPS, or an uploaded ground-based ephemeris). The AutoCon™ system is embedded in the Mongoose-5 (MG5) EO-1 spacecraft computer. Interfaces are handled with one interface to the C&DH system. This is used for the ingest of GPS states information, AutoCon™ commanding, EFF telemetry, and maneuver commands for EO-1 as well. The FQ algorithm needs input data for the current EO-1 state, the target state, and the desired state. These data are provided by

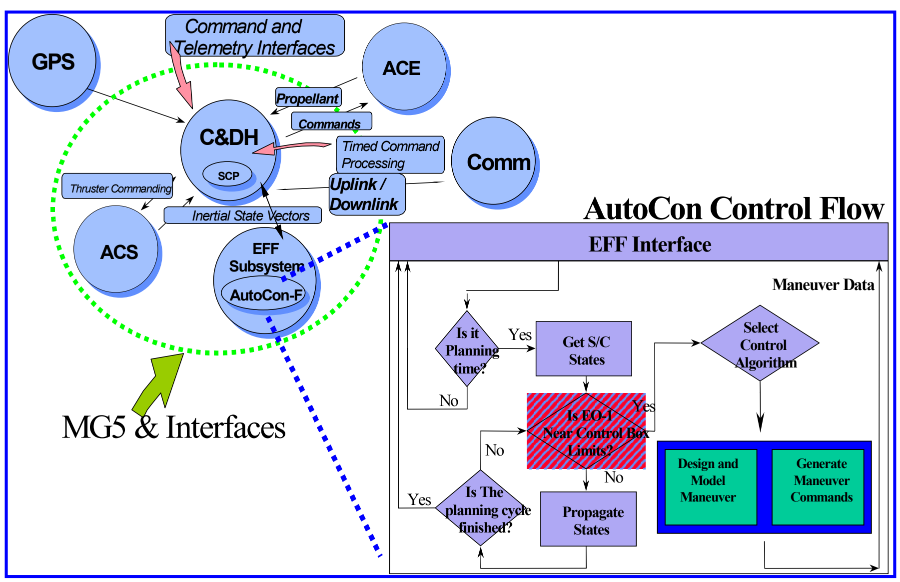

Figure 2. EFF Functional Diagram

AutoCon™. AutoCon™ takes the current EO-1 and uploaded Landsat-7 states and then propagates these states for a user-specified fraction of the period. Autonomous orbit control of a single spacecraft requires that a known control regime be established by the ground that is consistent with mission parameters. That data must then be provided to the spacecraft. When orbital perturbations carry the spacecraft close to any of the established boundaries, the spacecraft reacts (via maneuver) to maintain itself within its error box. The system is currently set to check the tolerance requirements every 12 hours. Form this point AutoCon™ propagates the states for 48 hours (a commandable setting) and will execute a maneuver plan if needed.

The overall size of the code was designed to run on the Mongoose-V within limits of ~600K lines and utilized CPU only over 4 seconds time periods. The size of the AutoCon™ system can vary depending on its utilization. That is whether propagation is required for predictable maneuver planning and forecasting and if a selectable method for determining the location and time of the maneuver is necessary. This size and execution speed will vary on the implementation in other spacecraft computers.

2.3 ALGORITHM MODES

There are five EFF maneuver control modes onboard EO-1 as shown in Figure 3. All control modes were verified onboard during this validation process. These modes were established to allow an incremental validation of the system performance, data interfaces, and maneuver computations before commands were generated onboard for an executable maneuver. Modes 1 and 2 were validated in a functional test while modes 3-5 were validated as executed EO-1 maneuvers. Modes 1 and 2 provide for the testing of the onboard interface and basic functions. These modes were executed in the initial validation process. Modes 3, 4 and 5 were executed to validate the maneuver planning process was correct and lead up to the full autonomous maneuver planning.

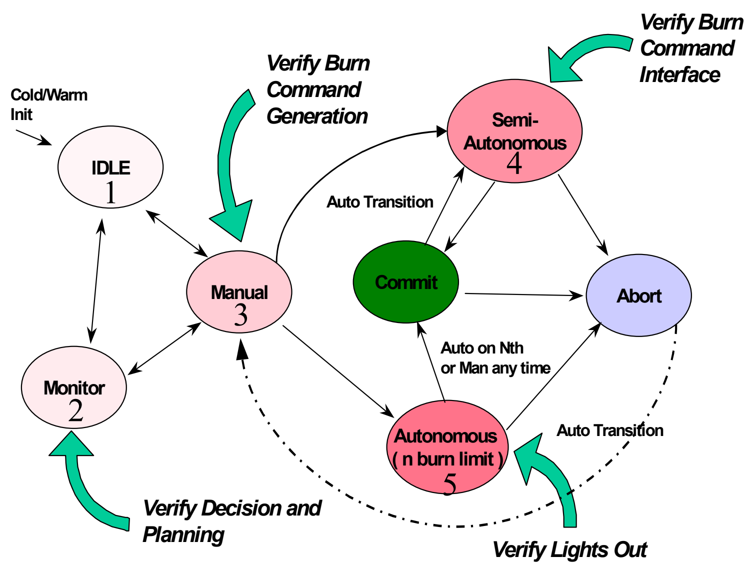

Figure 3. EFF Commandable Modes

2.4 ΔV COMPUTATIONS AND QUANTIZED MANEUVERS

The computation of the EO-1 maneuver ΔVs was performed using a sequence of two methods. The first method uses the FQ algorithm for the calculation of the maneuver to reach the targeted position relative to Landsat-7. Subsequently, a simple velocity-matching maneuver is then performed once the targeted position is attained. The FQ algorithm could also be used, but in an effort to simplify onboard processes, as no state propagation is necessary, a velocity matching method is employed. This velocity matching is computed from the predicted difference in the velocity of the EO-1 transfer orbit and the targeted state at the target position.

The EO-1 spacecraft propulsion system was designed so that the minimum maneuver duration is one second with larger burns selectable at one-second increments. This means that commands generated either onboard or on the ground will undergo a rounding of the maneuver duration based on the computed ΔV. For example if a maneuver is such that the computed maneuver duration is 5.49 seconds, the commanded maneuver will actually be 5 seconds, and a 5.51 second duration would become 6 seconds. This results in a quantized maneuver duration for each maneuver and thus the achieved Keplerian trajectory will differ slightly from the targeted trajectory. To compensate for this effect the final ΔV is adjusted. The velocity match is perturbed slightly to compensate for the position error resulting from the prior maneuver's quantized burn duration. This allows the targeted orbit's SMA to be achieved with a trivial sacrifice of eccentricity.

This FQ algorithm is part of AutoCon™ which features flight software that is capable of autonomously planning, executing, and calibrating routine spacecraft orbital maneuvers. The autonomous formation flying control software AutoCon™ builds on this existing capability for the maneuver planning, calibration, and evaluation tasks. AutoCon™ uses a fuzzy control engine, ideal for this application because it can easily handle conflicting constraints between spacecraft subsystems.

2.5 FOLTA-QUINN ALGORITHM CONTROL

The Folta-Quinn (FQ) algorithm needs input data of the current spacecraft state, which it uses to compute the target state, and the desired state (see ref x). These data are provided by AutoCon™, which takes the current state of the control spacecraft and calculates its orbital period. It then propagates this state for a user specified fraction of the period. This propagation provides the location of the control spacecraft at the target epoch. User specified offsets are applied to this state to create the target state. The target state is then propagated back to the epoch of the initial state, producing the desired state. This procedure creates the required inputs to the GSFC algorithm.

Establishing the desired state of a spacecraft's location is as varied as spacecraft missions themselves. Autonomous orbit control of a single spacecraft requires that a known control regime be established by the ground that is consistent with mission parameters. That data must then be provided to the spacecraft. When orbital perturbations carry the spacecraft close to any of the established boundaries, the spacecraft reacts (via maneuver) to maintain itself within its error box. Once an error box is provided to the spacecraft, no further ground interaction is required. Enhanced formation flying (EFF) takes the next step up the technological ladder by permitting the spacecraft themselves to establish where their own control boxes should be. This requires cooperation between all the members of the formation, and therefore a depth of communication between all the individual satellites that is not practical (or in some cases even possible) from the ground. This may occur through cooperative "agreement" by controllers of all the spacecraft in the formation or by maintaining a relative position from a designated 'lead', or by some hybrid of these two methods.

The AutoCon™ flight control system ingest data from additional sensors and spacecraft subsystems such as propulsion, groundtrack, navigation, and attitude data. It then is possible to autonomously generate, analyze, and execute the maneuvers required to initialize and maintain the formation between Landsat-7 and EO-1. Figure 2 shows a functional diagram of the AutoCon™ system. Because these calculations and decisions are performed onboard the spacecraft, the lengthy period of ground-based planning currently required prior to maneuver execution will be eliminated. The system is general and modular so that it can be easily extended to future missions. Furthermore, the AutoCon™ flight control system is designed to be compatible with various onboard navigation systems (*i.e.* GPS, or an uploaded ground-based ephemeris). The enhanced formation flying technology will demonstrate the capability of EO-1 to fly over the same groundtrack as Landsat-7 within +/-3 kilometers at the equator while autonomously maintaining the formation for extended periods to enable paired scene comparisons between the two satellites.

2.6 ORBIT MECHNANICS OF EO-1 FORMATION FLYING

In Figure 4, EO-1 starts a formation at the red dot located behind Landsat-7 by 450 kilometers and above by approximately 50 meters. Due to the differences in the accelerations from atmosphere drag and spacecraft design, the EO-1 satellite orbit decays faster than that of Landsat-7. While above Landsat-7, EO-1 is drifting away from Landsat-7. After several days of atmospheric drag, EO-1 will be below Landsat-7 and will drift towards it. When EO-1 is outside the required separation distance or if the Landsat-7 satellite has maneuvered away, EO-1 will autonomously compute and perform a maneuver to reposition it to an initial condition to repeat the relative motion and meet science data collection requirements.

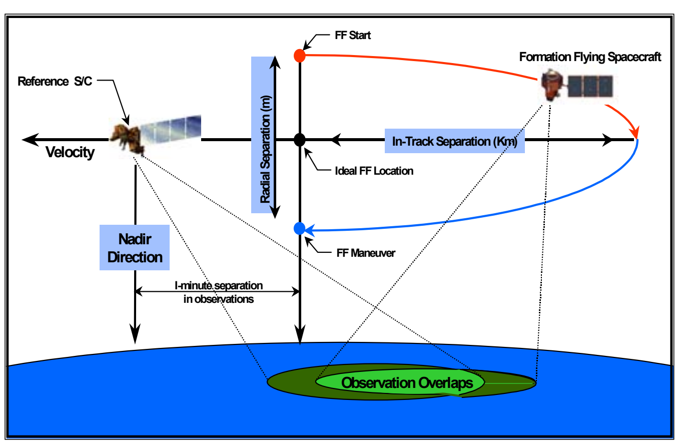

Figure 4. Orbit Mechanics of EO-1 Formation Flying

3. TECHNOLOGY VALIDATION

The EO-1 software validation certifies that all software requirements have been properly implemented and that the Enhanced Formation Flying (EFF) software meets all operational objectives. This section summarizes the approach used to accomplish these goals. The core AutoCon flight control software was qualified by executing a series of test plans, test data, and test scenarios. The results of each stage of validation were checked and documented. These activities have inputs from both the developers of AutoCon and the EO-1 ACS software engineers. Quality assurance were integrated into each stage.

3.1 GROUND VALIDATION PROCESS

The qualifications of the processes that were used to monitor validation are by: analysis, inspection, test, and demonstration. The requirements by which the test show qualification are by ACS external interfaces, functionality, sizing, timing, and tractability. The validation of each of these tests was performed at the following levels. Please note that Levels 1-4 are the ground verification process required to support onboard, level-5, validation of EFF. To date, all levels, 1-5, have been successfully completed.

- Level-1: AutoCon, using a PC or workstation environment to develop, test, provide high fidelity simulations, and proof of concept fuzzy logic rules.
- Level-2: Virtual Simulation, using a virtual simulation of the ACS with an embedded AutoCon core architecture flight code design to test the interfaces, telemetry, and commands with the ACS.
- Level-3: Software Test Facility, using a full spacecraft simulation of the ACS and GPS data to test AutoCon. Test all interfaces to the ACS and C&DH for telemetry and commanding. Performed on a Mongoose breadboard with supporting hardware.
- Level-4: FlatSat, testing of the AutoCon flight code on flight hardware and ACS system software.
- Level-5: Operational testing/validation of the core AutoCon flight code. These tests require a minimum amount testing to verify proper execution of the AutoCon flight control system.

To minimize associated test costs associated with these tests, the following approach was recommended.

- For each functional requirement develop scenarios that were executed for the mission.
- Develop system test for each scenario
- Develop system unit, integration tests for EO-1 AutoCon to develop a system checkout matrix
- Perform system tests for the mission scenarios and catalog results in matrix

The EO-1 maneuvers were computed onboard under a single system architecture called AutoCon, which employs separate maneuver decision/design modules or algorithms. AutoCon will control execution of the modules through an onboard mode switch, and perform constraint evaluation via fuzzy logic control. The AutoCon specifications were levied on the industry partners in order to facilitate uploading algorithms, patches, scripts, and required tables during the mission. Data and processing requirements from any potential industry partners were assessed during this initial phase of the technology. Figure 5 shows the ground development and test architecture used to verify the AutoCon executive, its interfaces, and the FQ algorithm. The software and hardware architecture is specified in Table 1.

3.1.1 AutoCon Executive and Fuzzy Logic Validation

Validation of the core AutoCon architecture executive was performed during the first year of the EO-1 mission development. This build is the system level control of all of the enhanced formation flying algorithms. The objective was to test the fuzzy logic control and the development of the overall architecture. The test ensure that the input, output, CPU memory, storage, processing speed requirements and the interface to the ACS provided data performs as expected and that control were invoke at the proper time for maneuver algorithms.

3.1.2 Required Data and Necessary Measurements

The data required to validate AutoCon are listed below from reference x (the AutoCon / ACS ICD). Fuzzy logic and fuzzy rule sets are the primary data requirements. Secondary data requirements are real data sets of EO-1 position state vectors from the EO-1 GPS orbit determination solutions and the Landsat-7 state vectors from the uplink of these vectors. The

ACS provides data in memory locations for input to the fuzzy logic control. Output files for placement into the interface with the ACS for telemetry were exercised.

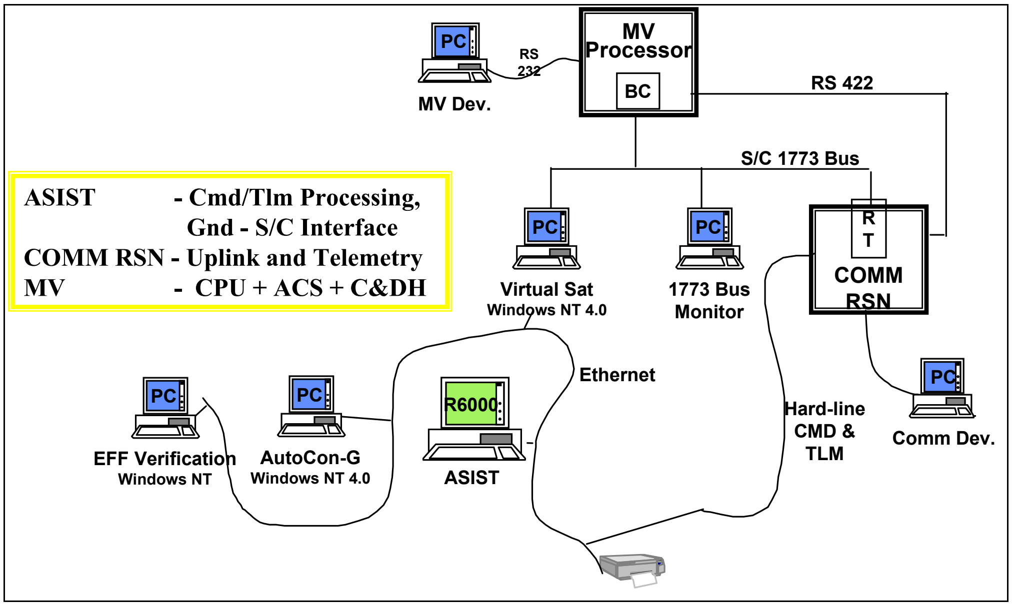

Figure 5. EFF Ground Validation

3.1.3 Approach

The validation approach is to execute AutoCon onboard with these input data values listed and allow AutoCon to process the data using the control algorithms. These algorithms both notify the ACS and ground through telemetry of a maneuver and invoke the maneuver planning algorithms within AutoCon. The validation shows that the fuzzy logic properly resolves conflicting constraints; that AutoCon can ingest the data from the ACS correctly for internal use; and that the interfaces with the ACS for all telemetry and command is working correctly. The final result of the validation is that the telemetry output confirms the maneuver decision has selected a proper time for a maneuver. Also, the validation proves the interface to AutoCon via ACS uplinked tables functions properly and confirm the required memory sizing of the onboard computer

3.1.4 Ground Testing Results

The results were that AutoCon returned a maneuver required flag and related information for the planning of the maneuver. There are not any interface errors. The AutoCon software runs within the tolerance specified for the memory requirements and timing requirements of the onboard computer. The validation verified the AutoCon interface to the ACS. An analysis of the downlinked telemetry shows the data provided though memory to the AutoCon system and the execution of the high level AutoCon system in terms of fuzzy logic, system control limits and flags was as expected. An indication by AutoCon that the data for the maneuver algorithms has been generated and control passed to the correct maneuver process is expected. The results are that the data within the telemetry data packets match the ground generated data. The differences between the ground and onboard AutoCon are expected to meet the values due only to difference in the software (constrained software run times or precision) and hardware (PC based versus Flight hardware). Scenarios for the validation address each difference.

3.1.5 Supporting Integration and Test (I&T) Data

Supporting I&T data of propulsion data, health and safety data, and other constraint data uplinked for AutoCon control were required. The input data includes preloaded fuzzy rule set and constraint checking limits. The validation requires that these data be commandable for a complete checkout of this algorithm. The validation requires software and hardware used for independent checking of orbital data, the use of the ground operational version of AutoCon for the validation of the fuzzy logic and rules, and the use of the Hammers Co.'s VirtualSat and the Flight Software Testbed for checking of all interfaces and the associated timing requirements.

TABLE 1
Supporting I&T Hardware and Software

Data Validated	Software	Hardware
Orbital Data	Freeflyer	PC/Windows-NT
Interface Checkout	VirtualSAT	PC/Windows-NT
AutoCon-Ground	AutoCon	PC/Windows-NT
Table Loads, Algorithms, etc.	Flight S/W TestBed	PC/Workstations
Telemetry Data	Telemetry Processor	EO-1 Control Center H/W

3.1.6 Rationale

The reasoning for this validation is to test the control methodology of the AutoCon executive through the processing of the fuzzy logic rules and the fuzzy logic engines. The difference expected are discussed above are to be minimal and only due to implementation in the spacecraft specified hardware software.

3.2 EFF ONBOARD VALIDATION

The onboard validation planning process originally assumed the Landsat-7 maneuvers occurred every 2 to 3 weeks. The reality was that Landsat-7 performed maneuver every 3-4 weeks and then for a period frequently at 1 week intervals. The requirement to maintain a one-minute separation between EO-1 and Landsat-7 was always met, but frequently EO-1 maneuvered before a complete 'revolution' of the formation cycle. The validation test centered on the following areas.

3.2.1 Validation of Interfaces and Algorithm

The purpose was to collect Loral Tensor (GPS) and S-Band Tracking Data as soon as Loral Tensor receiver is tracking. The intent here is to analyze GPS characteristics and test GPS accuracy against S-Band tracking orbit determination. The Tensor data will be fed into AutoCon-Flight (F)-NT, PC version of AutoCon-F, for refinement of the smoother setup. This data provided the first GPS performance measurements. Smoothing requirements and targeting accuracy can be ascertained from the measurements. A smoothing sample consists of two orbits of data minimum. Longer continuous sampling of Tensor data is not truly required but is highly desired. Collection of at least three smoothing samples is the minimum required with 2 days of nearly continuous data desired. This represented a good sampling of GPS conditions but more data will be required to prove this. Collection of the data should begin as soon as the Tensor is processing to give adequate analysis time for setup of the smoother operations to follow. For the best comparison, the highest accuracy S-Band tracking OD solutions are required to coincide with the sampling of the Tensor data. The data of interest from the Loral Tensor can be extracted from EO-1 VC-1 data replays using STOL proc. Note that this step does not require running EFF.

At this point testing is concentrating on basic EFF operation. **Checkout** of EFF with default scripts and tables. The intent here is to provide a quick functional confidence. When EFF is first turned on (taken out of it's idle state), a default script was executed to provide an overall functional checkout of the onboard software. One Autocon script was executed to perform this quick test and is described in procedure "EFF Quick Test of Autocon-F". Script 1 described in the procedure can be executed beyond the quick checkout to provide a simulated CPU loading. This will be the first occurrence of the heavy loading that EFF can produce.

Operate Smoother to setup and decide usefulness and need. The intent here is to analyze basic smoother operation and tweak its setup. EFF will be operated in the MONITOR mode during this phase and EO1 state data flows will be verified. A script will be loaded and the smoother will be operated providing smoothed solutions continuously. With the best case Tensor data, smoothing cycles will take slightly over 2 hours each to be generated. This will provide us ten plus solutions a day. During this shakedown of the smoother, daily analysis of the results will be performed by the EFF/Autocon design team. Depending upon the results obtained daily reconfiguration of the smoother may be required. The reconfiguration is accomplished by table uploads. After a workable smoother configuration is obtained, continuous operation of the smoother will be done for several days to verify successful operation. During this verification period, the highest accuracy S-Band tracking solutions are desired for the best comparison.

This script was executed in the **MONITOR** mode. Note that this is the first operation of EFF at a current epoch and most tables will need to be loaded. The data of interest from this phase can be extracted from EO-1 VC-1 data replays using STOL proc. At this point testing is concentrating on EFF and the proper transfer of state data.

Next we validated the GSFC Targeter in **MONITOR** mode for quick check out of data flow. The intent here is to extend the quick checkout performed in step two. During this phase, additional data flows will be checked out. This process can be as short as several passes. Operation of Autocon-F will expand to encompass most of the tables at this point. Telemetry and table dumps will be analyzed to ensure proper data flow. The EFF team monitored telemetry and analyze dumps of tables 122 through 127 for proper state information.

The Autocon script to run during this test is designated "eff_gsfc_test_1.autocon". Execute this script in **MONITOR** mode. See EFF/Autocon Initialization and Operation for description of how to bring up EFF and Autocon and execute a script. Note that this is a script change from the previous phase. All other data should be consistent and probably does not need to be reloaded. The data of interest from this phase can be extracted from EO-1 VC-1 data replays using STOL procs. Note that this step transitions to the next step by switching to monitor mode.

At this point testing was concentrating on the GSFC Targeter. Operate GSFC Targeter in **MANUAL** mode with a script planning maneuvers continuously. In true operation, planning would occur every 12 hours. The intent here is to analyze GSFC targeter performance on orbit. The continuous planning will maximize the number of burn plans generated. There will be one generated on the order of every 3 hours. The maneuvers generated will not be at the desired maneuver times and locations but rather will provide a more complete sampling of targeter performance. During this test, maneuvers of varying magnitude were generated as well as sampling varying orbital parameters. Several LS7 maneuvers occurred during this phase. At the completion of this phase the level of confidence in the GSFC Targeter's ability to formation fly EO1 has been established.

The Autocon script to run during this test is designated "eff_gsfc_test_1.autocon". Execute this script in **MANUAL** mode. See EFF/Autocon Initialization and Operation for description of how to bring up EFF and Autocon and execute a script. This is only a mode change from the previous phase and should only require that operation. The data of interest from this phase can be extracted from EO-1 VC-1 data replays using STOL procs.

The next step was to operate the GSFC Targeter in **SEMIAUTO** mode with a script planning the desired maneuvers. The intent here is to take an onboard generated maneuver and allow it to progress into the implementation phase to complete the data flow verification and test the EFF burn implementation. Essential item during this phase was the verification of the burn command sequence generation and the ATS patch of these commands. Operation in the phase should encompass 2 to 3 LS7 maneuvers or EO-1 only maneuvers. At the completion of this phase, the level of confidence in the EFF/Autocon process had been established with the ability to execute a script that will plan maneuvers around the input constraints and implement maneuvers successfully. The Autocon script to run during this test is designated "eff_gsfc_ops_1.autocon". Execute this script in SEMIAUTO mode. See EFF/Autocon Initialization and Operation for description of how to bring up EFF and Autocon and execute a script. Note that this is a script change from the previous phase. All other data should be consistent and probably does not need to be reloaded. The data of interest from this phase can be extracted from EO-1 VC-1 data replays using STOL procs.

The final step was to operate the GSFC Targeter in **FULLAUTO** mode. The intent here is to demonstrate autonomous maneuver capability and provide the Flight Operation Team an opportunity to independently operate EFF and the GSFC Targeter while the EFF design team observes. Operation in this phase should encompass two LS7 maneuvers as a minimum with 4 or more desired. The Autocon script to run during this test is designated "eff_gsfc_ops_1.autocon". Execute this script in **FULLAUTO** mode. See Procedure EFF GSFC Checkout for description of specific test. See EFF/Autocon Initialization and Operation for description of how to bring up EFF and Autocon and execute a script. Note: this is only a mode change from the previous phase and should only require that operation. The data of interest from this phase was extracted from EO-1 VC-1 data replays using STOL procedures.

At this point testing (July 20, 2001) is switching over to the JPL Targeter. Basic EFF/Autocon operations have been proven so we move straight into the targeter testing. It was planned to load the JPL Targeter into RAM while EO-1 is on the launch pad. Unfortunately, the JPL Targeter needed to be reloaded. The JPL algorithm uses the data from AutoCon just as the FQ algorithm does.

Operate GSFC and/or JPL Targeter in SEMIAUTO and/or FULLAUTO mode. The intent here is to provide the FOT an opportunity to independently operate EFF while further data on performance is collected. During this period either the JPL or the GSFC Targeter will be used dependent upon the results of the first years operations. Choice of SEMIAUTO vs. FULLAUTO is dependent upon the requirements of operations and the results of the first year's operations. Also the EFF/Autocon design team will begin to relax its continual observation and assume an on call posture. A key aspect for this experiment is that the FOT be able to operate the system. During this phase, the FOT should feel free to fine tune the process specifically in an effort to enhance the automation aspects. The tests conducted are shown below

Table 2 Validation Test Completion

Checkout and Monitor	Tests	Date	Complete
Uploads of Tables & Scripts	**Correctly Accepts Data**	**1/31/01**	**Yes**
Propagation With Forces	**Propagate for Duration**	**1/31/01**	**Yes**
Two-body Propagation	**Prop Model**	**1/31/01**	**Yes**
Conditional Constraint Check	**Formation Constraints**	**1/31/01**	**Yes**
GSFC Targeter	**Folta/Quinn Algorithm**	**2/02/01**	**Yes**
GPS Data Smoother	**GPS Position Smoother**	**5/01/01**	**Yes**
Manual Mode			
Conditional Constraint Check	**Formation Constraints**	**3/30/01**	**Yes**
GSFC Targeter	**Folta/Quinn Algorithm**	**3/30/01**	**Yes**
GPS Data Smoother	**GPS Position Smoother**	**4/12/01**	**Yes**
Semi-autonomous			
Conditional Constraint Check	**Formation Constraints**	**5/01/01**	**Yes**
GSFC Targeter	**Folta/Quinn Algorithm**	**5/01/01**	**Yes**
GPS Data Smoother	**GPS Position Smoother**	**5/01/01**	**Yes**
Autonomous			
GSFC Targeter	**Folta/Quinn Algorithm**	**7/0/01**	**Yes**
GPS Data Smoother	**GPS Position Smoother**	**7/01/01**	**Yes**
JPL Targeter Upload & Exec	**Upload of JPL Algorithm**	**7/01/01**	**Yes**

3.2.2 Validation Results and Period of Performance

The EFF scripts ran over a several month period, January 12th through July 12th, and generated over 600 maneuver test plans and nine successful maneuver commands to control the formation. The validation tests were divided into two areas, functional test of modes 1 and 2, and autonomous maneuver execution tests of modes 3, 4, and 5.

Functional Tests

Functional maneuver tests were planned in sets of three based on three propagation durations. GPS data was ingested 177 times while tables were uploaded approximately 30 times for script control, Landsat-7 data, and environmental data updates. The functional validation was accomplished by comparing several events and computations[7]. These tests included:

- EO-1 GPS and Landsat-7 state ingest
- EO-1 and Landsat-7 Propagation Events (Generate Target and Desired States)
- Folta-Quinn Targeting Algorithm Output
- Quantized Maneuver ΔV
- Three-axis maneuver ΔV
- Internal Calculations (Matrices, Variables, States)

Autonomous Tests

The maneuver execution tests were accomplished less frequently as they were tied to the operational maneuver timeline. The manual, semi-autonomous, and fully autonomous maneuvers were computed in much the same manner as the functional continuous tests with the following exceptions. Maneuvers were planned at a required maneuver epoch with the output used for planning of EO-1 formation flying maintenance maneuvers. The autonomous maneuver were planned with both a ground based S-band definitive orbit determination solution and the output of the GPS system onboard EO-1. The radial component targets varied over the demonstration as the atmospheric density was changing and the relative decay rates of both spacecraft needed to be considered. The radial target relative to Landsat-7 was 40m, 60, and 20m.

On January 12, 2001, the Enhanced Formation Flying (EFF) Experiment onboard EO-1 became operational. EFF was started in the modes 1 and 2 whereby GPS data would flow though the C&DH interface into the AutoCon^{TM} executable and maneuvers were computed continuously. Scripts and data uploaded via tables were enabled though the execution of EFF. With this data maneuvers were calculated at specified intervals. The overall computational interval was approximately 3 hours in duration and began with the ingest of a single GPS EO-1 state. This state, along with an uploaded Landsat-7 State, was then propagated onboard for durations of 12 hours, 24 hours, and 48 hours. Maneuvers were computed at the 12, 24, and 48 hour epoch marks. After the last maneuver was computed, a new GPS EO-1 state was ingested and the process began again. This enabled the continuous computation of maneuvers while verifying the ingest and data interfaces and propagation of states onboard EO-1.

3.2.3 Functional Validation of Modes 1 and 2

This section presents onboard and ground comparison results in terms of the absolute difference in the computed ΔV (cm/s) and the related percentage error for several maneuver scenarios. A total of 12 scenarios consisting of 3 maneuver sets (two maneuvers per set) for a total of 36 combined maneuvers were verified. The locations and epochs of these maneuvers were chosen randomly at approximately one per day over a three-week span. Figures 6 and 7 present the overall performance of each quantized maneuver as an absolute difference in the ΔV magnitude and its percent error. The mean value of the quantized difference is 0.0001890cm/s with a standard deviation of 0.000133 cm/s. These data show that there is excellent agreement between the onboard system and ground validation system. The larger residual in figure 6 is due to a 1-second quantization of a velocity-matching maneuver. This difference is due to the onboard system yielding a maneuver duration near the mid point that rounded down while the ground system rounded up. The difference is still small at 1.4%. The next figures, 8 and 9, present maneuver comparisons for the 3-D computation. This provides the comparisons for the total ΔV required to align EO-1 directly behind Landsat-7 and involves all three ΔV components of radial, alongtrack, and crosstrack.

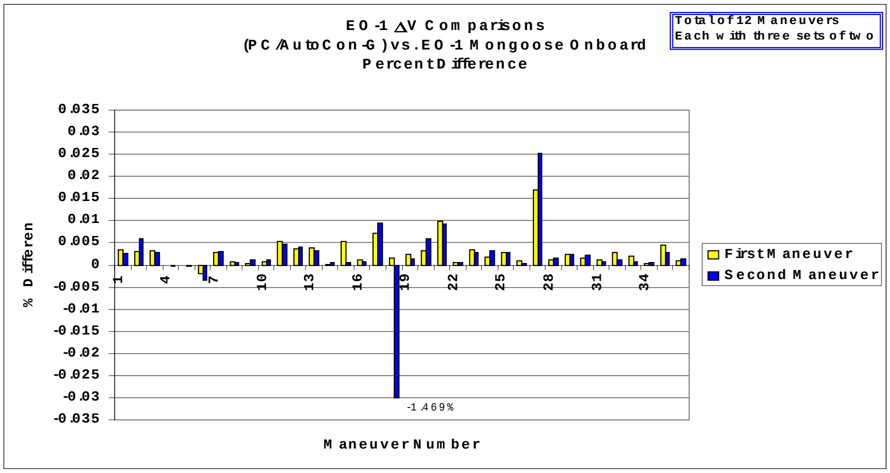

Figure 6. Percentage Difference in EO-1 Onboard and Ground Absolute ΔVs

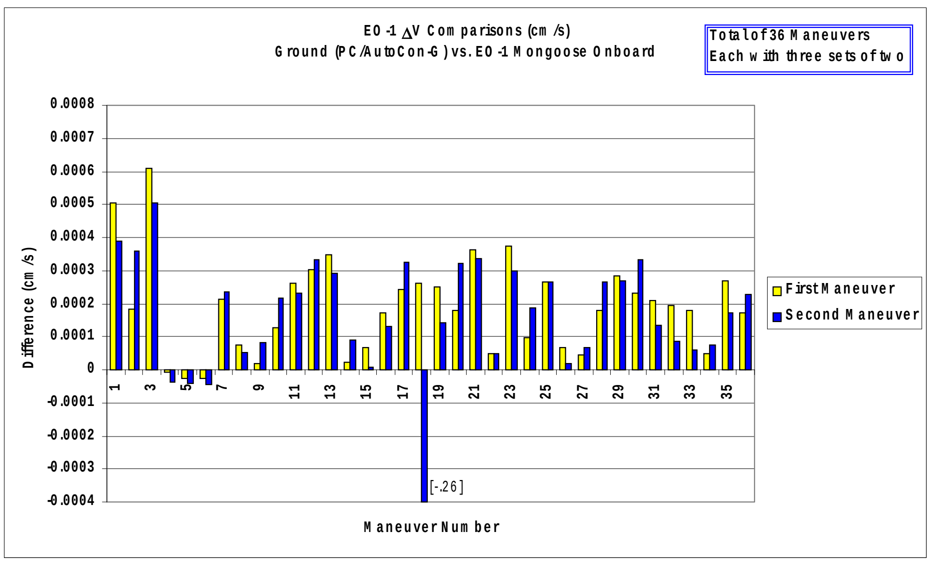

Figure 7. Difference in EO-1 Onboard and Ground Absolute ΔVs

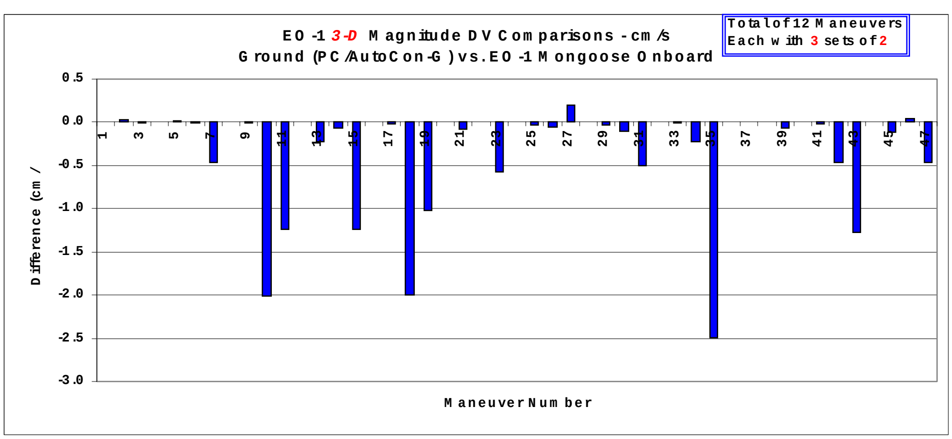

Figure 8. Absolute Difference in 3-D Onboard and Ground ΔVs

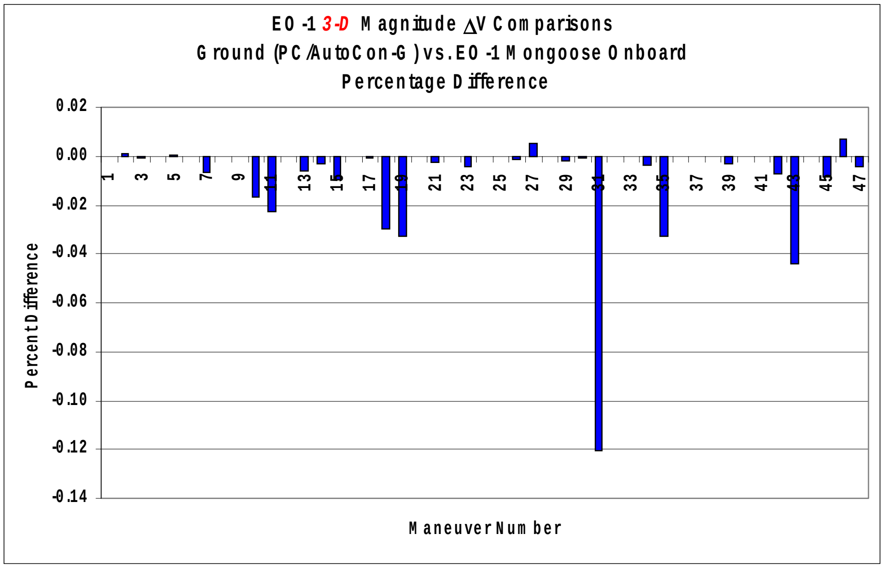

Figure 9. Percentage Difference in 3-D Onboard and Ground ΔVs

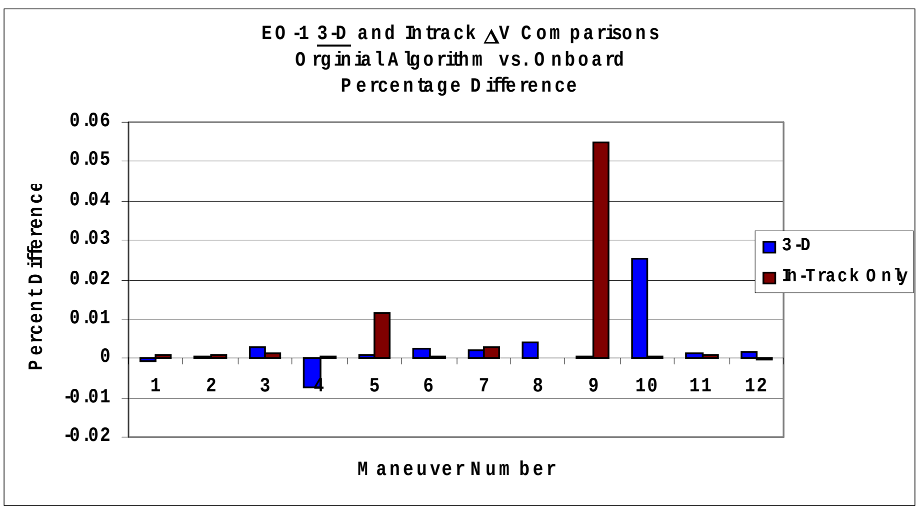

Figure 10. Percentage Difference in Original Algorithm and Onboard

Obviously the crosstrack component is the driver with the largest magnitude. The comparisons show only the total ΔV magnitude, as this is the only information available in EO-1 playback telemetry.

With the comparisons between the ground and operational onboard version of the EFF completed, a comparison to the original FQ algorithm code was then performed. This comparison was done only for the first FQ targeted maneuver of each maneuver scenario. The state data from the playback telemetry was input into a MATLAB™ script with the FQ algorithm computing the maneuver without any propagation. Figures 10 shows the difference as a percentage respectively for the 3-D ΔV and an alongtrack ΔV. The alongtrack ΔV was represented in the MATLAB™ script by using a local-vertical local horizontal coordinate system based on the input states, which is comparable to the EO-1 nominal attitude for maneuvers. The resulting ΔV difference gives a mean of 0.0727 cm/s and a standard deviation of 0.348058 for the 3-D and gives a mean of -0.03997 cm/s and a standard deviation of 0.278402 for the alongtrack. The mean percentage difference was 0.003 for the 3-D and 0.006 for the alongtrack. These results show excellent comparisons.

3.2.4 Functional Propagation Comparisons

The FQ Algorithm is dependent upon the generation of the target and desired states. These states are propagated onboard using a Runge-Kutta 4/5 with an 8x8 Geopotential model and a Jacchia-Roberts atmospheric drag model. The accuracy of the computed ΔV is dependent upon the accuracy of these propagated states. For EO-1, the states are propagated forward 1 and ½ orbits to compute the target state and then propagated 1 and ½ orbits backward to compute the desired state. As the desired state incorporates the longest propagation duration with a restart, a comparison was made in the onboard and ground states. The comparison results are shown below in figures 12 and 13. Figure 12 shows the position component and magnitude differences for six maneuver plans. Figure 13 shows the velocity differences. The maximum difference observed was 1.35 meters in the y-component of position and 1.4 cm/s in the velocity z-component. These small differences are still being investigated, but are believed to be the due to the integration into and performance of the EO-1 computer. The mean and standard deviations for position are listed in table 3.

Table 3
Propagation Mean and Standard Deviation for Desired State Computation

	X	Y	Z	Magnitude
Position Mean (m)	-0.02279	0.38221	-0.04550	0.79088
Position StDev (m)	0.07676	0.70684	0.45024	0.36886
Velocity Mean (m/s)	0.00007	0.00001	0.00040	0.00084
Velocity StDev (m/s)	0.00014	0.00049	0.00074	0.00039

3.2.5 Autonomous Maneuver Validation Results

A total of nine maneuvers were planned and validated in the manual, semi-autonomous, and fully autonomous mode with seven reported herein. All were used to plan a formation flying maintenance maneuver with the semi-autonomous and autonomous mode generating commands onboard that were used onboard as well. The commands generated onboard in the fully autonomous mode were placed in the absolute time sequence with other spacecraft commands at approximately 12 hours before the maneuver execution. The locations and epochs of these maneuvers were chosen to meet the EO-1 orbit and science requirements in response to Landsat-7 maneuvers or to an EO-1 maneuver to maintain formation. The results presented in Tables 4 and 5 show that there is excellent agreement between the onboard system and the ground validation system. Tables 4 and 5 present the maneuver mode and absolute ΔV difference and absolute percentage difference in the quantized and three-axis maneuvers. Table 4 gives results for the quantized maneuvers. Note that the percent error of the first ΔV computed from the Folta-Quinn algorithm (ΔV1) range from 0.000154% to 1.569%. The larger difference being the result of differences in the input target and desired states after propagation. The larger residual of the second velocity matching (ΔV2) is due to a 1-second quantization of a very small, 1.62 cm/s, 6 second long, velocity-matching maneuver. This difference is due to the onboard system yielding a maneuver duration near the mid point that rounded down while the ground system rounded up. Table 5 provides the comparisons for the three-axis ΔVs required to align EO-1 directly behind Landsat-7 and involves all three ΔV components of radial, alongtrack, and crosstrack. The ΔVs for these maneuvers range from 10.8 m/s to a maximum of 15.6 m/s. Again the comparisons are excellent with the range of percentage difference from the ground system at nearly zero to 0.66%. Additionally, a comparison was performed against the original algorithm, with excellent results as the percentage differences were all under 0.005%.

Table 4
Quantized Maneuver Comparisons

Mode	***Onboard ΔV1***	***Onboard ΔV2***	***Ground ΔV1***	***Ground ΔV2***	***% Diff ΔV1***	***% Diff ΔV2***
			Difference	***Difference***	***vs. Ground***	***vs. Ground***
	cm/s	***cm/s***	***cm/s***	***cm/s***	***%***	***%***
Auto						
Auto	4.9854078	0.0000000	0.0000001	0.0000000	0.00015645	0.00000000
Auto	2.4376271	3.7919202	0.0000003	0.0000002	0.00111324	0.00053176
Semi-Auto	1.0831335	1.6247106	0.0000063	-.0026969	0.05852198	-14.2361365
Semi-Auto	2.3841027	0.2649020	0.0000000	0.0000000	0.00011329	0.00073822
Semi-Auto	5.2980985	1.8543658	-0.0008450	-0.0002963	-1.56990117	-1.57294248
Manual	2.1915358	5.2049883	0.0000004	-0.0332099	0.00163366	-0.00022414
Manual	3.5555711	7.9318735	-0.0000003	-0.0272687	-0.00081327	3.57089537

Table 5
Three-Axis Maneuver Comparisons

Mode	***Onboard ΔV1***	***Ground ΔV1 Difference***	***3-axis ΔV1 vs. Gnd***	***Algorithm ΔV1 Diff***	***3-Axis ΔV1 vs. Alg***
	m/s	***cm/s***	***%***	***cm/s***	***%***
Auto					
Auto	10.8468	-0.0005441	-0.0000502	0.0003217	0.0000297
Auto	11.8633	0.0178726	0.0015066	-0.0101756	-0.0008577
Semi-Auto	12.6416	0.0311944	0.0024677	0.0091362	0.0002867
Semi-Auto	14.7610	0.1888158	0.0127932	0.0000000	0.0001196
Semi-Auto	15.3797	-0.2526237	-0.0164231	-0.0633549	-0.0045164
Manual	15.5790	10.4109426	0.6682668	-0.0117851	-0.0007565
Manual	15.4749	0.0018465	0.0001193	-0.0307683	-0.0021934

3.2.6 Maneuver Propagation Comparisons

As with the functional validation, a comparison of the propagated states used in computing the targeted and desired states is made. Figure 11 shows the comparisons of the inertial positions (x, y, and z) for the target and desired states. These states are computed using the same models as discussed in the functional validation. The largest difference can be seen in the columns marked 10-12. These differences occurred in the first semi-auto and last manual mode maneuvers. All the differences are less than 500 meters in all components with a standard deviation of less than 177 meters and less than 50 meters if the largest difference is excluded. Even so, these variations contributed in the differences between the onboard algorithm and the ground. The interval of propagation for these states are 13 hours for the manual maneuver modes and less than 2 hours for the semi-autonomous or fully autonomous mode.

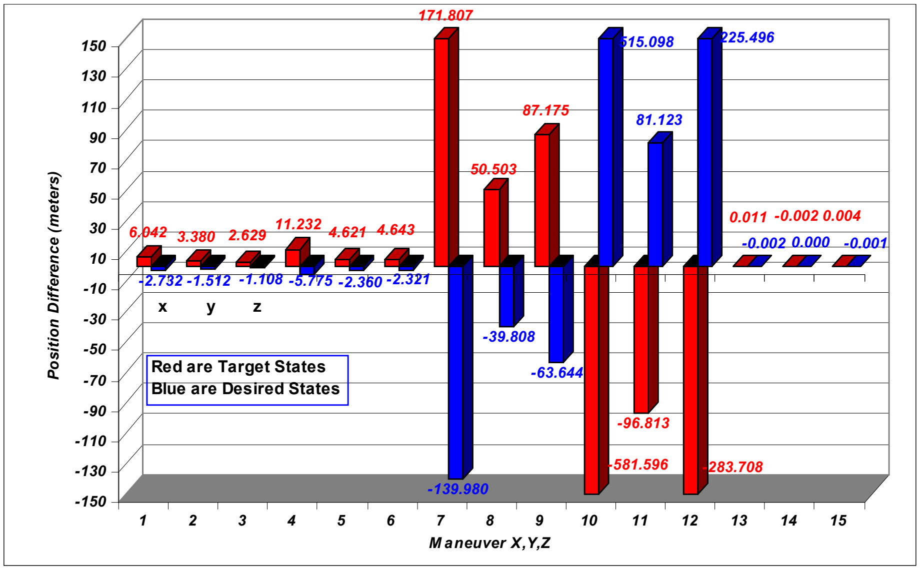

Figure 11. Target and Desired Propagation Position Differences

3.2.7 Independent Performance Assessment: EO-1 Formation History of Relative Motion and Keplerian Orbit Parameters

The following relative motion and Keplerian parameter plots are taken from the definitive ephemeris of EO-1 and Landsat-7 orbit determination process as an independent check to verify that the formation requirements of 450km with a tolerance of 75km (+/- 42.5km yields 407.5km to 492.5km) and the ground track of +/-3km are meet. Additionally, one can observed that the relative eccentricity and semi-major axis of the frozen orbit eccentricity was also maintained as a result of the formation flying maneuvers. Figure 12 shows the general formation flying evolution of the alongtrack and radial components presented in a Landsat-7 centered rotating coordinate system with the radial direction (ordinate) being the difference in radius magnitude and the alongtrack direction (abscissa) being the arc between the position vectors.

Figure 13 shows effect on the mission groundtrack by the formation flying maneuver and that it meets NMP requirements. The figure shows both EO-1 and Landsat-7 groundtracks as an offset from the exact world reference grid. The time span is over the duration of the formation flying demonstration of 5 months from February 2001 to June 2001. At the beginning of the demonstration, EO-1 maneuvers only occurred in response to Landsat-7 maneuvers as the formation cycle were EO-1 exceeded the front of the control box was not completed before a Landsat-7 maneuver was required. Figure 14 shows the alongtrack separations over the demonstration duration. Figure 15 shows the semi-major axis evolution in which one can

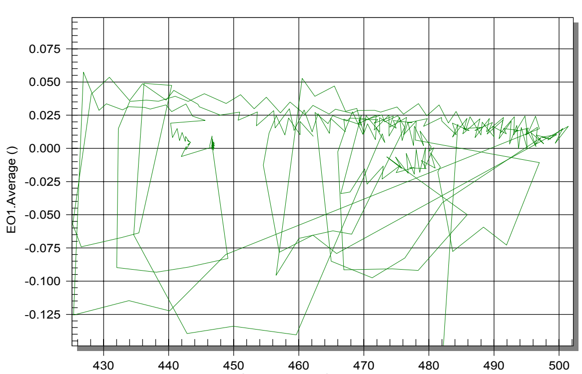

Figure 12. Relative Radial vs. Alongtrack Separation

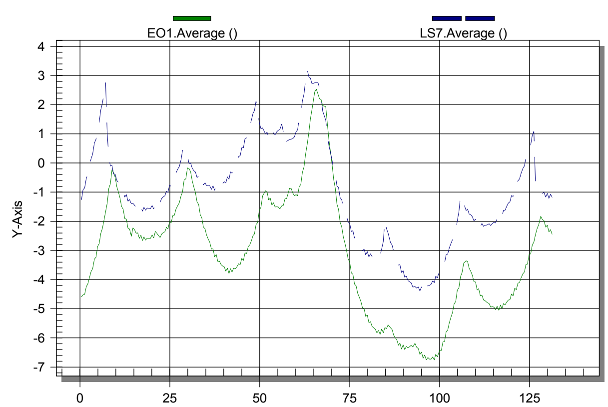

Figure 13. Ground Track Separation

see the effects of the differential ballistic properties of each spacecraft. Figures 16 and 17 show the frozen orbit eccentricity and argument of periapsis. The data for these plots was generated independently from the formation flying system and further show that the formation flying demonstration was a success.

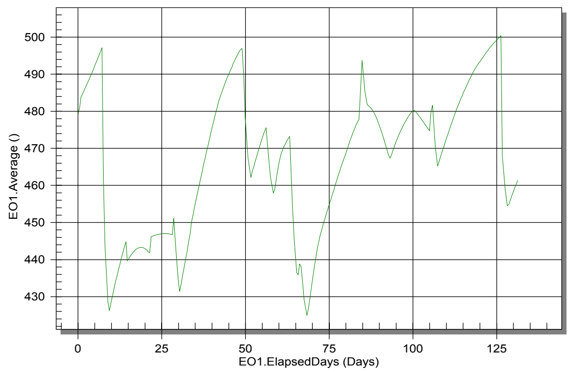

Figure 14. Alongtrack Separation vs. Elapsed Time

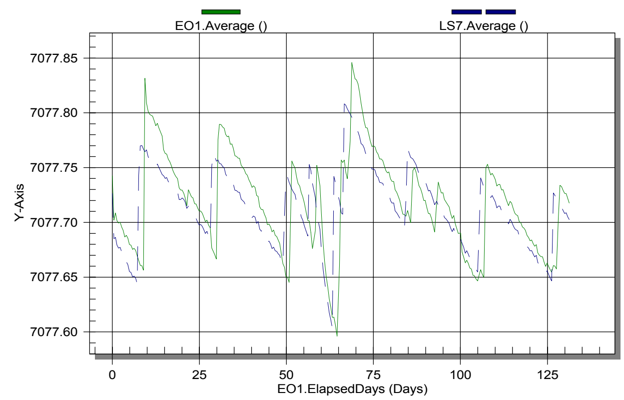

Figure 15. Semimajor Axis Profiles

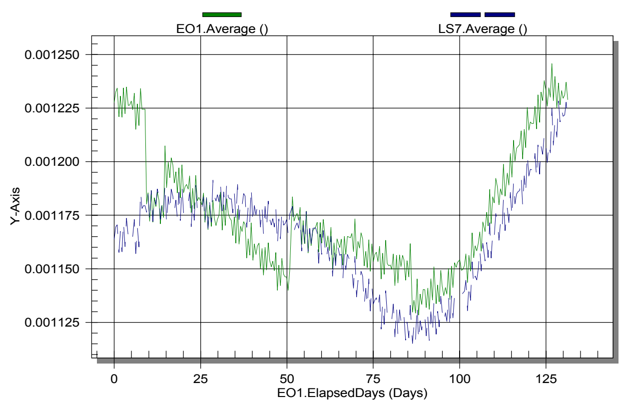

Figure 16. Eccentricity vs. Elapsed Time

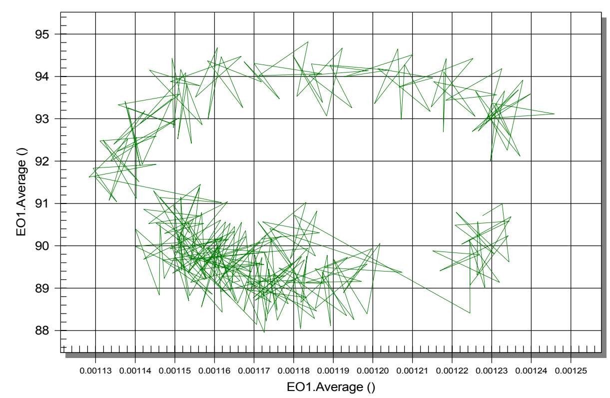

Figure 17. Eccentricity vs. Arg of Periapsis

4. APPLICATION POSSIBILITIES

Recent discoveries in areas of climate changes, the Earth's space environment, Weather predictions, Space weather, and investigation of planets beyond the solar system are drivers for the implementation of formation flying spacecraft. The diversity in the collection and measurement types of science data related to these areas is expanding. These diverse areas include:

- Viewing: Temporal and Spatial
- Collection Types: Large Scale Apertures, Multiple Pointing, Multiple In-situ, Imaging
- Measurements Types: Spectrum, Low Temperatures, Fields
- Pointing Accuracy: Repeatability, Stability, and Control.

Using this technology, significant improvements in science, space-based interferometery can be made. It can be used to increase the number of instruments comprising the system and eliminating the restrictions imposed by the use of physical structures to establish, maintain, and control instrument separation. Formation flying enables extensive co-observing programs to be conducted autonomously without complex multi-instrument observatories and extensive ground support.

Another area of interest for formation flying is instrument calibration and correlation. Such as with the EO-1 technology demonstration, the EO-1 spacecraft was required to fly in a way to allow scene comparisons. Also better performing instruments and the associated increased data and miniaturization will drive onboard and formation requirements. The need for inter-satellite communications for data distribution and sensor cooperation is also becoming a reality with the advanced crosslink applications such as PIVOT and LPT sponsored and developed by GSFC. The need for unique geometrical views from various orbits (sensor webs and unique non-Keplerian orbits) which include low earth orbits, elliptical orbits, libration point orbits, and unique orbits. An example of these science types of needs are: Bi-Directional Reflectance Flux under the Leonardo formation and X-ray detection using the Constellation-X mission.

There is also a need for image comparison and calibration achieved through close distance between S/C looking through the same atmospheric conditions at same location. Landsat-7 and EO-1 maintain a constant separation of 1-minute in time between each other while imaging the Earth. The challenges for these types of mission include autonomous maneuver control and autonomous navigation.

Future missions include formations such as those of the constellation-X mission that utilizes multiple S/C to observe the same target black holes, galaxy clusters formation, and missing matter S/C deployed and maintained to a relative position and attitude in the same reference orbit. Here the reference orbit is a libration orbit. The challenges here are

- Autonomous Maneuver Control
- Autonomous Navigation
- Attitude Control
- Mission Design.

Another mission is Maxim A Formation of Two Spacecraft To Image A Black Hole. Maxim Combines Both Constant Separation and Constant Attitude/pointing. The Detector S/c Must 'Fly' Around the Optics Continuously During an Observation. The associated challenges:

- Complex Closed-Loop Autonomous
- Maneuver Control
- Autonomous Absolute and Relative Navigation
- Precise Attitude Pointing and Control
- Mission Design
- Inter-Spacecraft Communication.

5. TECHNOLOGY INFUSION OPPORTUNITIES

Upcoming GSFC Earth orbiting mission infusion opportunities include any Earth observing mission that requires instruments either to fly in a formation or constellation. Also, another benefit to the NMP technology is the capability to perform simple orbit maintenance or sma maintenance or orbital corrections such as inclination maneuvers. That is to follow a desired semi-major axis using any propulsion system effort, such as small, near continuous maneuver or less frequent large maneuvers to maintain orbital conditions. It can obviously be applied to a requirement to view the same or similar areas, such as those of the EOS-PM train. Missions such as Picaso/Cena, Leonardo are prime examples of the formation applications while the Global Precipitation Monitoring mission (GPM) is a prime example of autonomous orbit control. Also missions to libration orbits for interferometry such as Maxim, Constellation-X, SPECS, and others can use this technology directly with changes only for the differences in the dynamic properties of the orbit. . As the technology is a three-axis control and uses AutoCon for the system level executive and interfaces it has numerous applications to any autonomous control requirements.

6. LESSONS LEARNED

There are many lesions learned from the integration, test and validation of the EFF. These are listed below in brevity.

Development

- EFF software interface is linked with C&DH & ACS. This lead to ACS controlled formats and timing issues.
- The use of MAVN fixed to resolve load problems.
- New version of a linker delivered to help resolve load problems.
- Continued Linking ASIST Displays to STOL procedures and RDLs.
- VirtualSat development to incorporate EFF.
- Continued Developing Test Plans.
- GPS Smoother under testing and independent evaluation while EFF developed.
- EFF ASIST displays being modified to better match ACS displays during tests.
- PROM load problems.
- Make sure all EFF/AutoCon data is properly initialized and get other system tasks to initialized their data.
- Resolve top 64K PROM load restriction.
- Determine why build is limited to 1.5MB
- Continue Developing Test Plans and Operational Scenarios as tests were executed.
- Smoother Evaluation not completed on time
- Integrating GPS Smoother
- Complete RDLs and STOL Procedures

In the Flight Software test lab

- Working Flight Software Lab Access for Spring '98 I&T
- VirtualSat and ASIST used to Verify/Validate EFF algorithms and I/F with ACS and C&DH. i.e. Telemetry packet generation, AutoCon Propagation and maneuver planning.
- Flight S/W TB verified actual processor loading and Test Procedures
- FSWTB test performed as short burst, load commands and execute at a convenient time. Verify the loading, data transfer and I/F to the C&DH.
- Combine test with ACS test sequence data and feed results into Virtual-Sat.
- End-to-End Full demonstration required at least twice.
- At least one GPS Load Test was planned.

EFF Internal Safety Implementation

- 48 Hour Notification to Ground on All EFF Generated Burn Plans.
- Monitor Mode Allows Burn Prediction and Planning to Verified.
- Manual Mode Allows Command Generation for Burn Implementation to Be Verified.
- Semi-autonomous Mode Allows Table Load and SCP Interface to Be Verified.
- Autonomous Mode Can Restrict EFF to "N" Burns to Mitigate a Runaway.
- Other External Safety
- Burns Limited to " ~ 20" Seconds by ACS Table Load and Limited to "~ 60" Seconds by Stored Command Sequence. This Is Changeable

Other Tests:

AutoCon-F Numerical Benchmark Testing
- AutoCon-F Was Benchmarked Against AutoCon-G for Each Build

AutoCon-F MV Testing
- Will It Fit and Execute on the EO-1 MV Processor?
- EFF/AutoCon-F Interface and Numerical Accuracy Testing Performed on the Test String From October 1998 to August 1999

EFF/AutoCon-F Testing on EO-1 (>20 Hours of Testing Onboard)
- EFF/AutoCon-F Successfully Executed on EO-1 in April 1999
- Round 1 of CPT in July Found Increasing Time Required for Maneuver Planning and Unacceptable CPU Utilization
- Round 2 of CPT on September 1 Passed All Test Criteria
- EFF/AutoCon-F Successfully Executed During Thermal Vac in October 1999
- Round 3 of CPT on December 4

GPS Smoother Testing
- Conducted on the Test String Using Simulated Tensor Data
- Scheduled for Spacecraft Testing on December 7, 1999 Using Real Tensor Data From Simulated GPS Constellation

7. SUMMARY

Using the formation flying algorithms developed by the Guidance, Navigation, and Control center of GSFC, onboard validation has shown that the EO-1 formation flying requirements can be easily met. To ensure the accuracy of the onboard FQ algorithm, several comparisons were performed against both original analytical calculations and ground based FQ numerical computations using AutoCon™ for given initial onboard-generated states. The FQ algorithm was validated by direct inputs of the initial taken from the onboard system. The ΔV results agree to millimeters/sec level for the numerical tests which include the effects of propagation. This validation effort establishes the following;

- A demonstrated, validated fully non-linear autonomous system for formation flying.
- A precision algorithm for user defined control accuracy.
- A point-to-point formation flying algorithm using discretized maneuvers at user defined time intervals.
- A universal algorithm that incorporates.
    1. intrack velocity changes for semimajor axis control,
    2. radial changes for formation maintenance and eccentricity control
    3. crosstrack changes for inclination control or node changes
    4. any combination of the above for maintenance maneuvers
- Proven executive flight code.
- A system that incorporates fuzzy logic for multiple constraint checking for maneuver planning and control.
- Single or multiple maneuver computations.
- Multiple / generalized navigation inputs.
- Attitude (quaternion) required of the spacecraft to meet the ΔV components

8. CONCLUSIONS

The GSFC GNCC's Folta-Quinn formation flying algorithm is a innovative technology that can be used in a closed-loop design to meet science and mission requirements of all low Earth orbiting formation flying missions. The algorithm is very robust in that it supports not only benign groundtrack control and relative separation control, but also demanding three-axis control for inclination and non-Keplerian transfers. To best meet the NMP requirements, this innovative technology is flying onboard the EO-1 spacecraft. The algorithm was successfully integrated into AutoCon™ for ground support validation, closed-loop onboard autonomy, as well as operational support. The application of this algorithm and the AutoCon™ system to other NASA programs is unlimited, as it applies to any orbit about any planet and can be used to fully explore the NASA mandate of faster, better, cheaper spacecraft.

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